CONVECTED CHARGE IN THUNDERSTORMS

B. B. PHILLIPS

Atmospheric Physics and Chemistry Laboratory, ESSA, Boulder, Colo.

ABSTRACT

The charge transport within thunderclouds by the convective motions of the cloud is examined. In the presence of the primary positive dipole, shielding charge distributions are formed within the lower and upper cloud boundaries as the result of ion conduction from the free air and ion capture by droplets and precipitation in peripheral cloud layers. Cloud droplets positively charged by the conduction current to the cloud base are lifted by the updraft into upper cloud volumes where they contribute to the positive pole of the primary dipole. In turn, precipitation developing in the cloud top carries negative charge to lower cloud levels during fall under gravity forces. The role of water accumulation in the upper cloud is shown to be an important factor in establishing the non-neutralizing current paths in upper cloud layers. The charge transport by the convection mechanism is believed to be a major current flow of storms. The role of other thunderstorm electrification mechanisms is only briefly considered.

1. INTRODUCTION

Preceding papers have discussed the charge distribution that develop within the cloud boundary layers of thunderstorms [14, 15]. The growth of the positive dipole charge distribution within the central structure of the storm establishes an electric field inside and outside the cloud. Both the cloud and the air surrounding it are conducting and in the presence of the radial component of the electric field a current flow occurs. The air is much more conducting than the cloud and the primary charge flow in the vicinity of the cloud boundary occurs from the motion of ions to the cloud surface from the free air. Within the cloud, the ions are attracted to the polarization charges on the cloud droplets. As a result, the inflowing ions are captured within peripheral cloud layers, forming a shielding charge distribution at the cloud boundary of sign opposite that of the primary positive dipole charges within the cloud. The magnitude of the shielding charge is greatest over the base and top of the thundercloud where the radial component of the field of the central dipole charges is greatest. The total charge in the upper cloud and cloud base shielding layers are comparable in magnitude to the charges of the primary dipole. It seems certain that the shielding charges are real features of thunderstorms since in the presence of the primary dipole charges within the cloud, the shielding layers establish themselves within a time period controlled by the conductivity of the free air adjacent to the cloud boundary. Thus the positive shielding charge about the cloud base is established within approximately 1 min. while the upper negative charge requires only 10–15 sec. These time periods are probably short compared with the time cloud elements remaining within the boundary layers of the cloud structure.

The charge captured on cloud particles in the peripheral cloud layers, however, is convected along with the cloud particle current. It has been suggested by previous authors [3, 18, 24] that the convective currents are so directed as to enhance the primary thunderstorm dipole charge distribution. A large part of the positive screening charge deposited on cloud drops at the base of the cloud will be carried into the upper cloud volume by the updraft. In turn, precipitation particles will be negatively charged in the upper shielding layer and during their fall earthward will carry negative charge into the lower cloud.

There is little doubt that vertical convection through the base can carry large quantities of the lower screening charge upward. In the upper part of the cloud, the mechanism of charge transfer is not so simple. Estimates of the charge concentrations in the shielding charge layer have suggested that the region proposed for negative charging of the precipitation particles is limited to a narrow lamina at the cloud surface. Gunn [3] indicates that the thickness of the charge layer within cloud at 10 km. is from about 10 m. to a few hundred meters. Vonnegut et al. [19], by a different argument, estimates the thickness of the upper shielding layers to be only about 3 m. If this were so, only a small transfer of charge by the precipitation mechanism could result since only the very lightest precipitation elements will penetrate upwards into the uppermost regions of active charging and these will not fall from the region with appreciable velocities, i.e., the transfer rate of precipitation particles through the charging region will be low.

The analysis of the thickness of the shielding layers given by the author [15] shows the upper charge layer is as much as 1 to 2 km., varying with the particle size and concentration. The measured continuing current, approximating 1 a., which flows to the tops of thunderclouds [19, 20] can 1) contribute to the shielding negative charge distribution; 2) discharge to the positive current flowing upward within the cloud; and/or 3) contribute to a negative precipitation current which passes earthward within the cloud. The present paper considers these current flows together with the cloud and precipitation mechanisms acting within thunderstorms.

2. PRECIPITATION AND CLOUD DYNAMIC MECHANISMS IN THUNDERSTORMS

In its simplest form, the thunderstorm is analogous to a fountain. The cloud water is carried upward by the air motion in the central updraft. In the vigorous central updrafts the terminal velocity of initiating droplets is far less than the updraft velocity. The speed of the updraft and the relative slowness of the initial coalescence-accretion mechanism of drop growth combine to produce the large water contents observed at considerable heights in the upper structure of thunderstorms.

It is important to recognize that the precipitation elements growing in the uprising cloud flow act to modify the cloud-precipitation regime in two major respects. First, the accumulation of precipitation serves as a collecting screen to greatly reduce the cloud droplet density within the cloud volume passing upward through the region of most active particle growth. Second, in the upper cloud levels where the thermal buoyancy forces are small or negative, the precipitation forces a horizontal divergence of the cloud flow. Within the deflected cloud-air stream, precipitation particles continue to grow with lateral displacement outward from the central updraft core where they finally fall under gravity forces. Within still higher cloud levels, the vertical updraft and the cloud liquid water content is greatly reduced.

The reduction in cloud water content as the air passes upward through the precipitation follows straightforwardly from first principles. The distribution of larger size particles in cumulonimbus is given by Jones [7] from data taken on meteorological research flights of Britannia aircraft. For particles in the size range from 0.5-mm. to 1.5-mm. radius, the observed maximum and mean concentration in thunderstorms is 1.0×10^{-3} cm.$^{-3}$ and 1.4×10^{-4} cm.$^{-3}$ respectively. If we assume the mean concentration reported by Jones is equal to the concentration of 1.0-mm. particles within the middle and upper levels of the updraft, then (for a collection efficiency of 100 percent) for this single-radius particle distribution alone 63 percent of the cloud water will be captured in passage upward through only 2.3-km. height. It may be noted that this particle concentration of particle density 0.6 gm./cm. (reported density from Jones) represents a water content of near 0.59 gm./m.^{3}

The variation of the updraft velocity w with height is given by

$$w \frac{dw}{dz} = g \left(\frac{T - T'}{T'} - \frac{W}{\rho} \right), \qquad (1)$$

where g is the acceleration of gravity, T and T' are the temperatures of the updraft and the environmental cloud-free air respectively, W is the liquid water content per unit volume, and ρ is the density of the updraft air. In upper cloud levels near and above the maximum updraft the second term in the right summand dominates; first, because the temperature of the updraft approaches the temperature of the environmental air, and, second, because the precipitation may accumulate since it is falling into air of greater density and greater upward velocity. If in these cloud layers the temperature term is negligible compared with the final term, then for a given horizontal lamina we can write

$$\bar{\rho}(w_2^2 - w_1^2) = 2gW(z_2 - z_1), \qquad (2)$$

where $\bar{\rho}$ is the mean cloud-air density in the height interval $h = (z_2 - z_1)$. The equation of continuity for a cylindrical wafer of height h and updraft radius r gives (for the air flux)

$$\pi r^2(\rho_1 w_1 - \rho_2 w_2) = 2\pi r V \bar{\rho}(z_2 - z_1), \qquad (3)$$

where V is the radial flow velocity. Assuming $\rho_1 = \rho_2 = \bar{\rho}$ (i.e., neglecting the expansion) the radial flow velocity originating from the presence of the supported water is from (2) and (3)

$$V = \frac{gWr}{\bar{\rho}(w_1 + w_2)}. \qquad (4)$$

This shows that a primary result of the accumulation of water mass in the updraft column is the initiation of a divergent horizontal flow greatly in excess of that provided by the simple expansion of the rising air. For example, if $w_1 \sim w_2 = 10$ m./sec. at 9-km. height where $\bar{\rho} \sim 400$ gm./m.^{3}, then the radial velocity at the radius $r = 2$ km. is $V = 15$ m./sec. if $W = 6$ gm./m.^{3} In this it should be kept clearly in mind that W is the total water content including cloud and precipitation; in this example we should expect the cloud water alone to account for 2 to 3 gm./m.^{3} of the total water.

The importance of (4) is to show that the effect of the "suspended" water is cumulative on the cloud air transports. The radial velocity increases with the mass of water and with distance from the central core of the updraft column. In the simplest case of vertical updraft without vertical shear, the water mass forming at the center of the updraft suffers no outward displacement. Precipitation formed away from the updraft axis is transported more and more rapidly outward from the axis as the distance from the axis increases, being carried horizontally with the cloud air flow. The surface area of the cloud top is expanded and evaporative cooling and mixing are increased. Such factors are contributing causes to the development of the horizontal shelves and the diagonal protuberances observed on cumulus structures at levels below the tropopause.

3. CONVECTIVE CHARGING MECHANISM AND CHARGE DISTRIBUTION IN THUNDERCLOUDS

In a preceding paper [15], it has been shown that the current density within electrified clouds is determined by the particle size and concentration and is independent of the electric field intensity. In thunderstorm clouds the particle distribution is such as to make the cloud essentially nonconducting. The continuity of current argument that has been used [9, 15] in demonstrating that the upper positive centers of thunderclouds contain of the order of +70 coulombs (C.), while the lower negative center con-

tains of the order of -400 C., is not wholly valid. The upper positive central core and the lower negative central core charges may each grow to large values, being limited by the processes of breakdown and charge convection. The shielding layers of charge at the cloud boundaries are similarly large and similarly limited. It is only the net charge in the upper cloud and the net charge in the lower cloud—the algebraic sum of the central core charge and the shielding charge in the upper or lower cloud—that we can expect to be limited by the conductivity. Here the limit is determined by the free-air conductivity, which thereby determines the net charge on the cloud as seen by an observer outside the cloud.

Within the cloud the overall charge distribution in the absence of convection and breakdown would more closely compare to a double negative dipole. The lower cloud possesses a distributed central negative charge slightly greater than a principally underlying positive shielding charge originating from the positive conduction current to the cloud base and the upper cloud possesses a distributed central positive charge slightly greater than a principally overlying negative shielding charge originating from the negative conduction current to the cloud top. The shielding charges are smaller than the central charges in the amount of charge in the central distributions that are tied by electric force lines that terminate either on the opposing sign central charges or on charges induced on the conducting earth and ionosphere.

In recognizing the large charge density established by conduction to the lower screening charge layer, it becomes immediately apparent that the cloud droplet distribution in the expanding central updraft carries a charge of large magnitude into the upper cloud. The bound charge on the cloud droplets at the cloud base, within the updraft, and within the resulting water "storage" region in the upper cloud volume constitutes the cloud positive charge distribution.

When the vertical motion of the updraft exceeds the terminal fall velocity of the cloud particles and the developing precipitation, the water storage volume necessarily develops atop the updraft. The most dense precipitation-cloud drop storage will occur with positive charge accumulation in the lower and central portion of of the water storage region on the updraft axis. During active precipitation growth periods (which follow from the strong updraft condition) the growth of the positive central core charge may be very rapid. This causes a large mass of dispersed positive charge in the upper cloud volume that is not discharging by conduction because of the low ion concentration of the cloud and is not sufficiently dense to cause lightning. It is reasonable to believe that it is this distributed charge which produces en masse the upper positive pole of the thunderstorm.

Immediately above and surrounding the core of positive charge exists the upper boundary layer shielding charge region. In this region the precipitation, cloud dynamic, and electrification mechanisms work in unison to produce a negative current flow from the conducting environment

to the precipitation. The growth of precipitation in the central upper cloud core causes a decrease in the cloud particle density in the upper cloud layers, both as a result of diffusional and associative type precipitation growth in the uppermost cloud layers and as a result of accretionary cloud drop capture in the primary precipitation growth region below. With the decrease in particle density, the negative ion flow is extended deep within the upper cloud, while the positive ion flow outward from the dense upper positive cloud core is negligible. The particle charge in the region of nonequal ion concentration in the presence of existing electric field E as given by [3] is (in e.s.u.)

$$Q = 3Ea^2 \left[\frac{(\lambda_+/\lambda_-)^{1/2}-1}{(\lambda_+/\lambda_-)^{1/2}+1} \right] \tag{5}$$

where λ_+ and λ_- are the positive and negative polar conductivities in the vicinity of the particle. The particle charge acquired near the diffuse inner surface of the shielding charge layer is large since this is a region of maximum electric field and maximum conductivity ratio. The negatively charged particles supported in this region are carried outward from the central updraft by the divergent flow of the cloud air. As this occurs, the charged hydrometeors pass first laterally outward and then downward through a region in which the space charge is negative and where the positive ion density is nil. The negative current carried by the precipitation will therefore not be neutralized but may instead increase with particle growth as a result of the capture and association of cloud and precipitation elements.

The strength of the negative current flow into the cloud upper boundaries is almost completely controlled by the convective mechanisms. In the absence of convective transport of the negatively charged particles by either gravitational or hydrodynamic mechanisms the negative current will approximate the rate of charge accumulation in the central positive cloud core. With these active transport mechanisms that develop with the precipitation growth, the charge in the shielding layer is reduced, the radial electric field at the cloud boundary is increased, and the negative current to the precipitation and cloud particulate distribution increases in an amount essentially equal the convected current. In this manner, the storm system develops a negative charging current that is carried downward outside the central cloud updraft by gravitational forces into the lower cloud where it acts to increase the flow of positive current to the cloud base. Figure 1 is a schematic representation of a developing storm system in the early stages of maturity.

4. NUMERICAL EVALUATION

Assume as initial conditions that a negative current of 1a. is carried downward by precipitation into the lower cloud volume. Several processes, which will be outlined later, act to accumulate the negative charge within the lower cloud. The charge accumulation rate is nearly at $dQ/dt = 1$ C./sec. The growing negative charge is bound to the positive charge in the upper cloud, to the positive
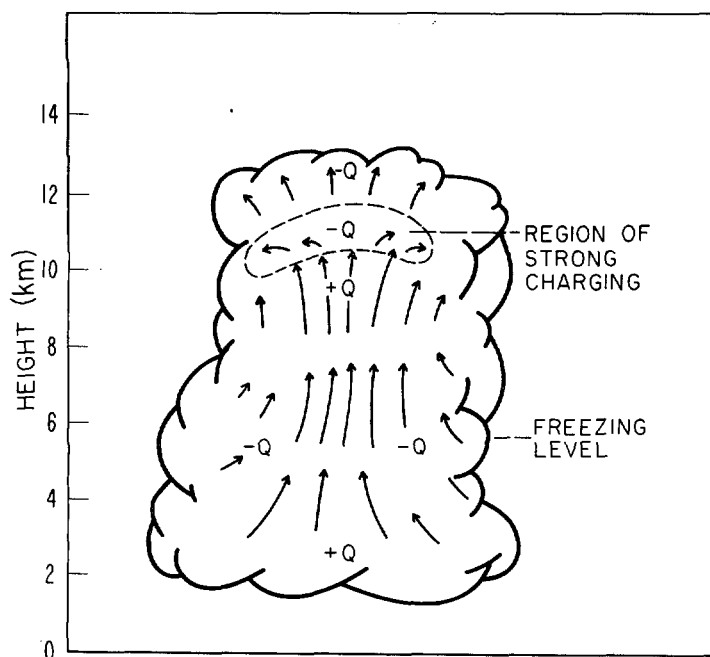
FIGURE 1.—Schematic representation of electrification in early mature stage of storm development.

PARTICLE RADIUS IN MICRONS

FIGURE 2.—Negative charging current as a function of particle radius for conductivity ratio, λ_+/λ_-, of 1/4, 1/10, and 1/100. Lower curves are for $\rho_w = 1.0$ gm./cm.^{3} and are for a pure water cloud; the upper curves are for $\rho_w = 0.125$ gm./cm.^{3} and are for a glaciating cloud.

charge developing simultaneously in the shielding layer within the cloud base, and to a lesser extent, to the positive charge outside the lower cloud boundary (principally on the earth's surface). We will assume that 50 percent of the accumulating negative charge is matched by a positive charge flow to the lower cloud boundaries and that 50 percent of this latter charge is deposited along stable cloud boundaries. The remaining positive charge flow amounting to 0.25 a. is deposited on cloud surfaces that ultimately share in the convective updraft motion of the storm. If the air flux into the storm is 2 km.^{3}/min. [22] and the mixing ratio is such as to yield 6 gm./m.^{3} during ascent, the water mass flow is 2×10^8 gm./sec. and the specific charge at the upper level of the updraft is 1.25×10^{-9} C./gm. If the liquid water content of the cloud volume is 2 gm./m.^{3} (i.e., a $3 \times$ expansion in lifting) then the charge density in the upper cloud is 2.5 C./km.^{3} and within the interior upper cloud volume of radius $r = 2$ km. the total stored charge approximates 84 C. The accumulation time is close to 6 min. In actuality, as a result of precipitation growth we would expect the liquid water content and the charge density to be somewhat greater toward the central cloud core and somewhat less radially away from the central axis of the updraft. If the total cloud and precipitation water content is 4 gm./m.^{3} in the central 10 km.^{3} of cloud then the total charge in this region alone is 50 C.

The negative current to and from the upper shielding layer depends on the updraft velocity, the efficacy of the precipitation and the lateral transport mechanisms, and the cloud particle size, shape, density, and concentration. These factors control the particle charge and the rate of water transport through the shielding layer. Since the charging time is near 10–15 sec., the shielding layer is always near charge equilibrium with respect to the central core positive charge despite the relatively energetic convective transport of water mass that results from the up-
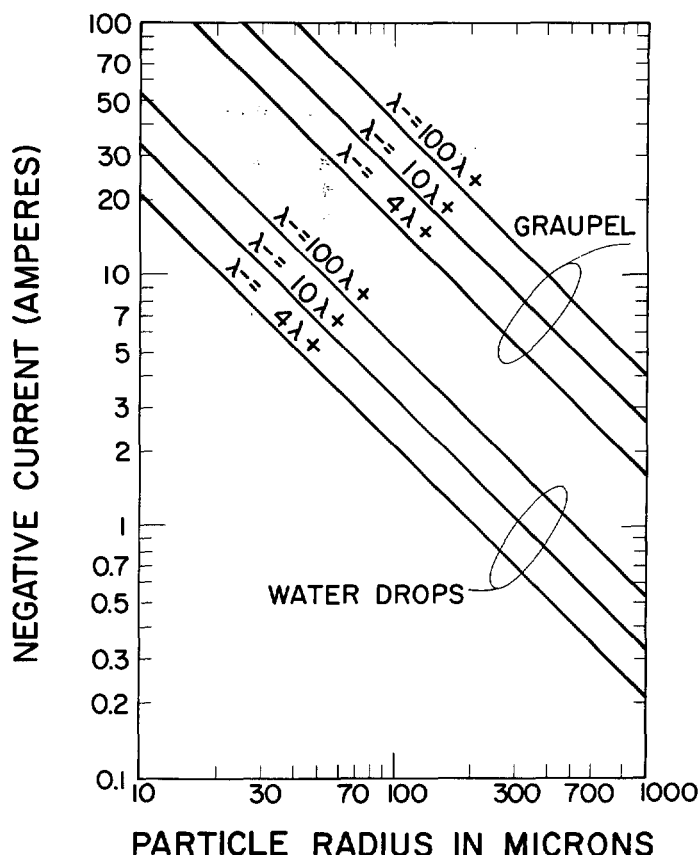
draft and horizontal cloud flow. Much of the water carried upward from the cloud base by the updraft is captured as precipitation near the upper central cloud core and is not exposed to the negative charging current passing inward through the upper boundary layer. The remaining fraction, f, of the water from the base is carried upward and outward by the dynamic flow through the negative charge region in the upper cloud. The specific charge (e.s.u./gm.) acquired is from (5),

$$\chi = \frac{9E}{4\pi a \rho_w} \left[\frac{(\lambda_+/\lambda_-)^{1/2} - 1}{(\lambda_+/\lambda_-)^{1/2} + 1} \right]. \tag{6}$$

The specific charge increases toward the interior of the shielding layer since both the field and the reciprocal of the conductivity ratio increase with cloud penetration. The field will be maximum and the factor in brackets will approach unit magnitude near the inner surface of the shielding layer where the lateral transport mechanism is most active.

The negative charging current from the upper shielding charge region is given as the product of the specific charge acquired and the rate of water transport through the region. If we assume that the air influx at the cloud base of 2 km.^{3}/min. transports water into the upper negative charging region at the rate of 2 gm./m.^{3} of input air (i.e., $f = 1/3$), and that the electric field in the charging regions is 4 stat. v./cm. (1200 v./cm.) then the charging current

is shown in figure 2 as a function of the droplet radius in the charging region. The three lower curves in this figure are computed for three conductivity ratios, λ_+/λ_-, of 1/4, 1/10, and 1/100 on the basis of $\rho_w = 1$ gm./cm.^{3} and thus represented the negative current for a pure water cloud. The upper curves are computed for the same conductivity ratios but for a particle density of $\rho_w = 0.125$ gm./cm.^{3} the observed mean density of graupel [12], and thus represent the charge transfer rate for a cloud glaciated principally by active riming. It is apparent that the total charging rate can be from one to several amperes in developing storms.

The total negative current to the upper cloud from the free air environment must be the sum of the current carried downward on the precipitation plus the current required to neutralize the inflow of positive charge on the cloud particles entering the shielding layer from below. Since in our estimate, only one-third of the water mass enters the shielding layer the net current required for neutralization is only 0.08 a. of the total negative current to the cloud top.

It should be especially noted that although the boundary layer charge discussion stresses the particle specific charge and total charge accumulation in the shielding layer, it is near the interface between the positive charge central core and the outerlying negative charge sheath where the primary transfer of negative current to the precipitation occurs. That the boundary layer charge distribution does not completely nullify the electric field outside the cloud and that a continuing current of the order of 1 a. flows to the cloud top is a measured result [20]. During the mature stage of the storm, the charge distribution in the shielding layer may be approximately constant. For an individual particle in the shielding layer the equilibrium charge acquired by the particle is determined by the equality of the positive and negative ion currents to the particle, i.e., when $I_+ = I_-$. For the assemblage of particles in the layer then the total currents to the particles are also equal, $\sum I_+ = \sum I_-$. The central positive core of the cloud is essentially nonconducting and the electric field is radially outward. The positive ion current is that resulting from ion formation in the layer itself, so that $\sum I_+ = qV$, where q is the rate of ion formation and V is the total volume of the negative shielding region. The negative current to the particles is therefore also limited to $\sum I_- = -qV$, and since ions are always generated in pairs it is evident that the total negative ion loss to the sheathing layer particle distribution is entirely compensated by the ion gain furnished by ionization. The continuing current at the cloud-air interface passes through the negative shielding charge distribution *without loss*. At the diffuse interface between the central positive charge core and the negative charge sheath the continuing current is arrested by the increasing density of the cloud particulate distribution. Here the electric field is maximum. Particles charged at the interface will not lose their charge rapidly when they are carried to higher levels (and lower fields) within the shielding layer because of the absence of positive ions in the shielding layer. These facts lend
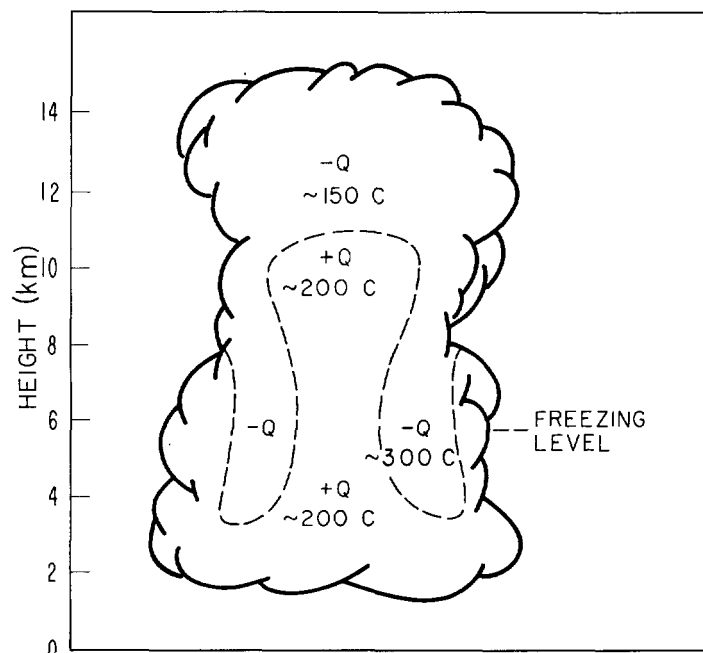

FIGURE 3.—Estimated charge distribution in a mature thunderstorm.

judiciousness to the value of $E = 4$ stat. v./cm. used in the computation of figure 2.

The overall charge distribution in a fully developed active thunderstorm may be estimated as in figure 3. The cloud system is of 10-km. diameter. A total positive charge of 400 C. is distributed within the cloud. A large fraction of this total is distributed about the quasi-static lower cloud boundaries and within the updraft column. The upper central core of the cloud is a region of positive charge aggregation containing perhaps a total of 200 C. distributed on the cloud and precipitation. The uppermost semispherical cloud cap possesses 150 C. negative charge. The negative gravitation-convective charge flow may approximate several amperes whereby the negative charge accumulation on the snow-ice-water precipitation falling to the lower cloud levels may reach 300 C. in a few minutes. This negative charge flow is chiefly outside the central updraft moving earthward at the fall velocities of the particles.

5. CHARGE ACCUMULATION AND ELECTRIC INSTABILITY OF CHARGE TRANSPORT

The accumulation of charge within the cloud boundary shielding layers and within the upper positive central cloud core has been outlined above. The negative charge accumulation in the lower cloud is believed to occur from three processes:

1) Snow growth in the region immediately above the freezing level. Below the $-15°$ C. level the combination of riming and clumping (the latter increasing near the zero degree isotherm as a result of the increasing wetness of the surface) will yield large structures of low density having low terminal fall velocities. The effect of these growth processes tends to aid particle and charge accumulation in the region near and above the 0° C. cloud level.

2) Drop breakage. Immediately below the 0° C. level the precipitation undergoes general acceleration downward as a result of the density increase accompanying melting. Drops which are, or become through continued growth, sufficiently large will break into small drops that fall at lower velocities and this tends to counteract the otherwise decreasing trend of the electric charge density and again accumulate charge at low cloud levels. This storage mechanism is not likely to be of great importance unless drop breakage is associated with selective charge transfer with respect to the smaller and larger drop sizes [5].

3) Partial evaporation of the precipitation mass in downdrafts. This is probably the most important of the negative charge accumulation mechanisms. From an analysis of the thunderstorm water budget based on observational data, Braham [1] finds that the biggest user of water mass in the thunderstorm budget is the downdraft. His data and conclusions pertain primarily to comparatively small storms, and indicate that only about 10 percent of the water vapor entering the cloud reaches the ground as precipitation. More recent results suggest that precipitation efficiencies of greater than 50 percent occur in large severe thunderstorms [2, 13]. A large amount of the water mass is lost by evaporation in sustaining the saturation within the cloud downdraft. We may expect that the charge accumulation efficiency of the thunderstorm mechanism is inverse to the precipitation efficiency. Weak storms with diffuse downdrafts permit a relatively large amount of charge to remain within the cloud volume; storms having downdrafts as a result of heavy precipitation will lose relatively less charge because the more vigorous downdraft motion will carry the released charge along inhibiting charge accumulation within cloud levels. Weakly developed storms will therefore have a higher efficiency for lightning production than storms with strong downdrafts, which may explain such features as the apparently high frequency of lightning from storms producing virga and the observation that "when the heavy rain begins the lightning frequency decreases."

The accumulation of charge in either the central core or shielding layer charge distributions is not necessarily the sole cause of the growth of electric instability and the resultant lightning discharge. If, for example, we examine the classical problem of the flow of charge along an infinite cylinder, the radial electric field at the surface of the cylinder is $E = 2\pi r\rho$ where r is the cylinder radius and ρ is the charge density within the cylinder. The current flow through the cylinder is given by $I = \pi r^2 \rho w$, where w is the velocity of charge transport along the cylinder. Eliminating ρ from the two expressions gives $I = (1/2) rwE$. This result can be applied to show the limitation on the charge flow within the convective currents in storms. In cloud air, the breakdown electric field strength may be reduced to $E_{max} \sim 20$ stat. v./cm. If we take the updraft velocity as $w = 10^3$ cm./sec. uniformly through an updraft radius of $r = 1.5$ km., then the maximum current transported upward without breakdown is 1.5×10^9 e.s.u. or 0.5 a. In turn, a surrounding annular column of negative charge convected downward by gravity can support

approximately four times this value being diminished by a slightly lower velocity (of fall) and increased by virtue of the greater radius and central core of positive charge. Somewhat larger currents would be indicated upon evaluation for the finite length of the charge columns in thunderclouds. Greatly larger currents can occur only with expanded cloud dimensions and increased transport velocities.

6. DISCUSSION

It is evident that a primary electrification mechanism is connected to the flow of water mass within the convective motion of thunderstorms. Droplets rising in the updraft carry positive charge from the lower cloud boundary regions into the upper cloud. During the turn around time at the top of the cloud fountain, a portion of the developing precipitation acquires a negative specific charge 10 to 100 times the specific charge carried on the positive cloud water distribution. A fundamental point is that the convective mechanism of charge transfer operating at the cloud base and cloud top are essentially separate mechanisms, which act in some unison but need not have equal charging rates. The magnitude of the conduction ion flow to the boundary layers separately depend on the rate of charge transfer from the cloud boundary charge distributions: the more active the convective mechanisms become, the greater is the demand for ion flow from the conducting free-air environment and the more active is the electrification mechanism. The upper positive charge core may in fact be viewed as a near static system supported in a nonconducting environment. Thus, the positive upward convected current may be only a fraction of an ampere whereas the negative current for strong convection may be measured in amperes.

Low particle concentration and large particle size appear critical to the current generating mechanism at the cloud top for two reasons. First, the shielding layer charge distribution is limited to no more than a few hundred meters if the particle radius is 20 μ or less, even for water contents as low as 0.1 gm./m.^{3} Thus the fraction of the water mass which is negatively charged at any moment represents a very low percentage of the total water mass of the cloud. The updraft velocity required to support such particles is negligible and the terminal fall velocities capable of transporting the charge downward from the sheathing layer at appreciable rates are absent. The boundary layer charge is likely to be lost to the anvil rather than to the precipitation. Second, the lateral transport mechanism that is associated with the divergent flow of water mass from atop the positive central core of the cloud depends linearly on the water content of the cloud. In the absence of lateral flow, the negatively charged precipitation originating in the upper cloud layers would fall into and neutralize the central upper cloud positive charge volume.

It is entirely reasonable to expect, however, that the coarse particle distribution occurs in the tops of cumulonimbus. Measurements in cirrostratus and cirrocumulus show particle structures commonly of dimensions 0.5 mm. to 2 mm. [21], while the existence of precipitation-sized

particles at cloud levels near the visual cloud top is supported by radar observations. For example, Jones and Marwitz [8] using a 3-cm. radar uncorrected for beam width have observed that the radar top is usually very near the visual cloud top both in developing, and in mature or dissipating cumulonimbus. The role of the water mass within convective clouds is believed to be a controlling factor in the development of the cellular and steady-state type thunderstorms; these interactions will not be discussed here, however.

The convective mechanism appears readily capable of accounting in large part for the charging currents believed to exist in developed storms. If the convective charge transport is to be interpreted as a primary charge separation mechanism, it is necessary to examine closely the initiating charge separation events that lead to establishing the primary positive dipole. To extend the argument to the developing cumulus structure requires that we resort to an argument as follows:

The initial growth of the cumulus structure aspirates upward the positive space charge that exists within the air below the cloud base. From measurements of the electric field gradient the positive space charge can hardly be greater than 10 ions/cm.^{3} in the mixed lower air that supports the initiating cumulus. If we consider a developing cumulus of volume equivalent to that of a sphere of 4-km. radius then the total cloud volume is 2.6×10^{17} cm.^{3} and the total intake charge approximates 0.43 C. The entire cloud remains nearly neutral since the positive charge flow upwards will be accompanied by a negative current flow that develops a screening charge distribution on the lateral and upper cloud boundaries. The initial charge separation occurs as a result of precipitation growth in the boundary layer volumes in the manner previously described abetted by the diffusion charging mechanism [4, 6] and the selective ion capture mechanism of Wilson [23]. We may expect these mechanisms to be active before appreciable electric fields develop within the cloud.

Two additional factors are important to the development of thunderstorm electrification: First, the mixing and associated cooling that occur at the cloud boundary in the tops of large cumuli aids in the initiation of ice particles and subsequently in the initiation of precipitation. Second, the pulsed-type growth followed by partial subsidence suggests the development into the cumulonimbus structure is accompanied by the peripheral shedding of small-sized negatively charged particles about the generally rising updraft. As observed by Ludlam and Saunders [10], "In clouds which are developing and reaching increasing height, it can sometimes be observed that eventually there are amongst the fragmentary residues of a cloud tower (which are evaporating) rather more persistent fibrous details which evidently consist of small precipitation elements." Certainly, we should expect that these particles that we have an opportunity to see only in evaporating cloud towers exist similarly within the more stable cloud boundaries. Such precipitation elements are not initially detected by radar according to their size and range. Thus the initial particle distribution, which has an appreciable "fall velocity" with respect to

the rising tower chiefly as a result of the tower motion upward, may go undetected for many minutes of slow particle growth.

The presence of 0.43 C. within a 4-km. radius sphere can produce only very weak fields of about 0.01 e.s.u. even in the absence of the screening charge neutralization. Thus the charge separation can be expected to develop at a rate perhaps one thousand times slower than had been calculated in figure 2. This possibly emphasizes the role of graupel-type growth in the early electrification of clouds since the specific charge for the rimed particle is nearly an order of magnitude greater than that of a liquid particle of the same dimension. Even so, in either warm or glaciated clouds, accretion occurs with the capture of cloud droplets that carry a high specific charge if they lie within the boundary layer volume. The negative charging current in initiating cumulonimbus will thus be of the order of 10 to 50 ma. which can "lower" 1 C. of charge in about 1 min. of cloud growth.

While the above argues for the presence of graupel as an aid in the initial electrification of clouds, Moore et al. [11] have observed that outward positive electric fields of 10–30 v./cm. are associated with vigorous growth periods of maritime warm clouds ($T > 273°K$). Periods of static cloud development or subsidence of the cloud tower were associated with weak, near zero fields. Such observations show that electrification processes are not dependent upon the presence of ice in the cloud structure.

Space does not permit an interpretation, based on the convective charge currents, of the extensive amount of thunderstorm data that are available from surface and airborne measurements within recent decades, but a recent analysis by Takeuti [16, 17] of field changes occurring during storms is extremely interesting in the present concept. Takeuti has found three types of thunderclouds: Type I predominately produces an upper-positive vertical dipole discharge; Type II, an inclined or horizontal discharge; and Type III, an upper negative vertical discharge. Type III is found likely to have a more or less thin distribution of negative electric charge on top. The path lengths of intracloud vertical discharges are usually 2 km. or less while the horizontal discharges are mostly longer. The electric charge neutralized in a cloud discharge often exceeds 100 C. and on the average *exceeds* the charge carried to earth by ground strokes. The height of the charge center neutralized by the return ground stroke (4 to 5 km.) was found not to *increase* with stroke order, in contrast to previous concepts, but instead often progresses laterally with successive strokes. The magnitude of the cloud discharge is very plausible on the basis of the large charges in the positive and negative boundary and central updraft regions. The ground stroke carries less charge because the lowest negative charge is being diminished in part by positive drop capture in the lower cloud levels and in part by discharge of the lower positive screening charge during the cloud to ground discharge process. The horizontal discharges should be expected along regions of electric stress about the positive updraft and particularly at the cloud base where high charge densities occur in near static boundary regions,

while the negative dipole with the thin negative charge distribution above corresponds to the upper level precipitation growth region charge distribution of the present model.

7. SUMMARY

The convective transport mechanisms in thunderstorms has been shown to yield charging currents that result from 1) the vertical lifting of positive charge residing on cloud droplets that have been electrified by ionic conduction at the cloud base, and 2) the gravitational downward transport of precipitation particles negatively charged by ionic conduction in the upper cloud. The charging mechanisms operate independently of the ice phase or point discharge but the processes will be considerably enhanced if these are present. Also, the estimated charging currents are of such magnitude that recourse to such mechanisms as splintering, ice-ice contact, induction charging, raindrop disjection, etc. is unnecessary (though not precluded) in accounting for the lightning discharge rates observed in storms. In the author's view, such mechanisms are present, but are perhaps not more fundamental to the thunderstorm generator. Charge transfer processes occurring during collision and break-up are in fact necessary to explain the positive and negative drop mixture within and below thunderclouds. These processes, however, tend to always leave an equality of charge on precipitation elements where the charge is most likely to be carried downward by successive drop capture and downdraft motion. It is by these other mechanisms and by the associated hydrodynamic processes that the thunderstorm is made far more complex than suggested by the present analysis.

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